International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 9, Issue 6, Dec 2019, 399–410

OPTIMISATION OF WIRE-EDM PROCESS PARAMETERS FOR ACHIEVING LOW SURFACE ROUGHNESS IN MACHINING OF IS 5986 FE 410 STEEL AND REGRESSION MODELLING

DEEPAK. D[1] & RAJENDRA. B[2]

[1]*Associate Professor, Department of Mechanical and Manufacturing Engineering,*
Manipal Institute of Technology, Manipal Academy of Higher Education, India

[2]*Professor, Department of Mechanical and Manufacturing Engineering. Manipal Institute of Technology,*
Manipal Academy of Higher Education, India

ABSTRACT

Non-traditional machining methods are popular in the recent era for machining of various profiles in different engineering materials. In this work, the effect of critical process parameters namely current (I_c), pulse-on time(T_{on}), pulse-off time (T_{off}), wire-speed (W_s) and voltage (I_v) on surface roughness (SR) is investigated while machining non-traditional machining methods are popular in the recent era for machining of various profiles in different engineering materials. In this work, the effect of critical process parameters namely current (I_c), pulse-on time(Ton), pulse-off time (T_{off}), wire-speed (W_s) and voltage (I_v) on surface roughness (SR) is investigated while machining of IS 5986 FE 410 steel by wire-electrical discharge machine (wire- EDM). The experiments were designed using Taguchi L16 arrays and results are analyzed using statistical methods. The process parameters such as Ic, T_{off} and W_s showed a significant contribution by 66.22 %, 13.77 % and 9.25 % respectively on SR. Further, the process parameters were optimized to obtain a minimum SR which produced in Ra values 1.480 µm at settings I_c -4 A, T_{on}- 40 µs, Ton - 10 µs, W_s- 1400 rpm and I_v- 80 V. Regression model is developed to predict the SR at different settings for the control parameters which predicted the response with average predication an error of 11.08 %

KEYWORDS: Wire-EDM, Material Removal Rate, Pulse-Off Time, Current IS 5986 FE 410 Steel, Wire Speed, Pulse-on Time & Voltage

Received: Sep 09, 2019; **Accepted**: Sep 29, 2019; **Published**: Oct 30, 2019; **Paper Id.**: IJMPERDDEC201934

Original Article

1. INTRODUCTION

The rapid changes in the market scenario demand the steels with enhanced quality, properties and performance capabilities to suit the design specification of the end products. Alloys of steel possess superior mechanical properties such as corrosion resistance [1–2], good hot workability and high toughness which made the material suitable for structural applications. In general, steel alloys are used in various applications including automobiles, ship building, boiler and pressure vessels, transmission towers, railways, oil and petrochemicals, coal and mining, general and heavy engineering machinery parts, etc. Machining of steel is challenging due to high affinity of work hardening, high toughness, low thermal conductivity and high fracture toughness [3–6]. Materials such as duplex stainless steel show the tendency for the formation of built-up edge. The adherence of material to cutting tool reduces the cutting speeds which affect the machining efficiency in the form of accelerated tool wear, poor surface finish and low dimensional accuracy [7, 8]. Although some of the complexities involved in conventional machining may be addressed by the non-traditional machining methods, there is limited literature available on machining characterization of steel and its alloys.

Satyanarayanan Raghavan et al [9] attempted laser tempering based turning process for machining of hardened AISI 52100 steel which is used for large wind turbine bearing. Initially, the hardened work piece surface was laser tempered and then conventional machining was made. The study showed that this method resulted in lower cutting forces and tool wear rate, higher Material Removal Rate (MRR) compared to conventional hard turning. Ali Alshemary [10] studied the different types of errors generated on cylindrical holes while machining of 2205 duplex stainless steel fabricated by the wire-electric discharge machining (EDM). Interactions between process parameters were found to be significantly affecting the diameter errors such as circularity and cylindricity. These errors are produced by non-uniform undercut and overcut which are controlled by settings to input parameters. Janaka R Gamage et al [12] studied the process level environmental effect of EDM process settings on machining performance of aluminium (3003) and steel (AISI P20) through time, energy, resources and emissions studies for each case. A considerable amount of energy consumption was found to occur during non-productive machining stages which particularly show the impact on the environment in the form of consumption of electrical energy (60%). Deepak D et al [13] optimized the current and pulse duration in electric discharge drilling of D2 steel using graphite electrode. The study showed that MRR and surface roughness were significantly influenced by the current. The optimum settings produced MRR 38.16 mg/min and surface roughness of 3.39 µm. Morphological of the cut surface showed the formation of globules due to machining. Further, the coefficient was established for predicting surface roughness for machining this material by EDM [13]. The authors also investigated the influence of abrasive water jet machining of D2 heat-treated steel [14]. It was found that at constant stand-off distance (SOD), the top kerf width was increased by 18% and the bottom kerf width was decreased by 25% due to increase in jet pressure in one pass machining. Further, surface roughness was also found increased at higher SOD and feed rate. Yingmou Zhu et al [17] studied the surface quality of stainless steel produced by blasting erosion arc machining. The results showed that the negative beam resulted in producing a highly rough surface (up to Ra - 55 µm), the heat-affected zone (HAZ) to depth about 13 µm from the machined surface and the formation of recast layer. The positive beam resulted in good surface finish (Ra 9.5 µm), the HAZ was lesser 5 µm and minimization of the recast layer. Klocke et al [18] investigated the Electrochemical Machining of 42CrMo4 Steel by numerical methods. The study detailed the micro-structure evolution process on surface topography in a passivating electrolyte system. The model helps to predict the surface topography for different process parameters and various initial microstructures.

This work investigates the effect of current, pulse-on time, pulse-off time, wire-speed and voltage on MRR while machining of IS 5986 FE 410 steel by wire-EDM process and optimise the settings. Also, based on the experimental results, a mathematical model is developed to predict the MRR for different input settings of the process parameters. This work is expected to help wire-EDM industries to choose the optimum setting for machining of IS 5986 FE 410 grade steel by wire-EDM.

2. MATERIALS AND METHODS

2.1 Experimental Set up and Specimen Details

Figure 1 shows the details of experimental set up. In the present work, experiments are performed using 2-axis (X-320 mm, Y-400 mm) computer numerically controlled wire-EDM made by Concord wire-EDM, India (Model: DK7732). Molybdenum wire (diameter: 0.16 mm) is used as tool electrode during the experiments. Mixture of soft water and gel is used as dielectric fluid. The resolution of the controller is 0.001 mm. The work piece used is IS 5986 Fe 410 steel. The

chemical composition and mechanical properties of the work piece is shown in table 1 and table 2 respectively. The carbon equivalent (CE) is determined based on ladle analysis as given by eq. (1).

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \tag{1}$$

Figure 1: Experimental Setup.

Table 1: Chemical Composition

Carbon	Manganese	Phosphorus	Sulphur	CE
0.20	1.50	0.035	0.035	0.45

Table 2: Mechanical Properties

Yield Strength	Ultimate Tensile Strength	Elongation
420 MPa	480–590 MPa	15%

2.2 Design of Experiments

The process parameters such as current, pulse-on time, pulse-off time, wire speed and voltage are chosen to study its effect on SR. The voltage is varied at two different levels and remaining parameters are varied at four different levels. Table 3 show the process parameters and their levels. These levels are chosen based on the trial experiments. Total degree of freedom required for the experimental design is 13, hence experiments are designed using L_{16} (4^5x1^2) Taguchi orthogonal array. Table 4 shows the experimental design. The experiments were replicated for two trials in each experimental condition. Thickness of specimens (5 mm) and the supply pressure of dielectric fluid were kept constant during experiments.

Table 3: Wire-EDM Process Parameters and their Levels

Parameters	Unit	Code	Level 1	Level 2	Level 3	Level 4
Current	A	I_c	3	4	5	6
Pulse-on time	µs	T_{on}	20	30	40	50
Pulse-off time	µs	T_{off}	5	10	15	20
Wire speed	RPM	W_s	175	350	700	1400
Voltage	V	I_v	80	90	-	-

Table 4: The Experimental Design and Corresponding Surface Roughness

	Settings of the Process Parameters					
	I_c	T_{on}	T_{off}	W_s	I_v	Average R_a
1	3	10	5	1400	80	6.82
2	3	20	10	700	80	6.98
3	3	30	15	350	90	8.80
4	3	40	20	175	90	9.20
5	4	10	10	350	90	7.82
6	4	20	5	175	90	10.12
7	4	30	20	1400	80	7.64
8	4	40	15	700	80	8.78
9	5	10	15	175	80	6.64
10	5	20	20	350	80	5.36
11	5	30	5	700	90	3.04
12	5	40	10	1400	90	2.60
13	6	10	20	700	90	6.82
14	6	20	15	1400	90	4.72
15	6	30	10	175	80	3.74
16	6	40	5	350	80	3.52

2.3 Measurement of Response

Test samples are machined for a length of 20 mm as per the experimental design shown in table 4. The work-piece is split and the roughness on the cut surface is measured across the cut surface using Taylor surtronic instrument. The sampling length of 10 mm is maintained during the measurements, the average Ra obtained in each experimental trial is tabulated in table 4. The cut surfaces of test samples machined at different settings of process parameters is shown in figure 2.

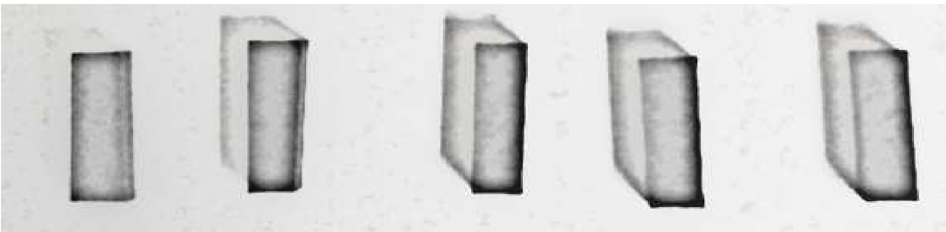

Figure 2: Cut Surface of the Machined Samples.

3. RESULTS AND DISCUSSIONS

3.1 The Effect of Process Parameters on Surface Roughness

The effect of current on surface roughness is shown in figure 3 (a). At current settings of 3 A to 4 A, the machining resulted in high SR in the average range of 7.95 µm to 8.59 µm. Further increase in current to 5 A resulted in reducing the SR up to 4.41 µm. The intensity of the spark energy (E) increased according to the equation, $E = I_v I_c T_{on}$. Higher current resulted in removing the materials with greater radius (r) i.e., $r \alpha E^{0.33}$. It is also observed in figure 3(f) that the spark frequency is decreasing with increasing levels of current. The combined effect of increasing the current and decreasing the spark frequency ($1/T_{on}+T_{off}$) resulted in melting the material over a greater radius and effective removal of removed material from the machining surface. This resulted in reducing surface roughness upto 48.66 % by increasing the current settings to 5 A during machining of IS 5986 FE 410 steel. Beyond current settings of 5 A, result showed a slight increase in SR (6.57 %) due to the very high spark intensity. This indicates the existence of the optimum setting to the current.

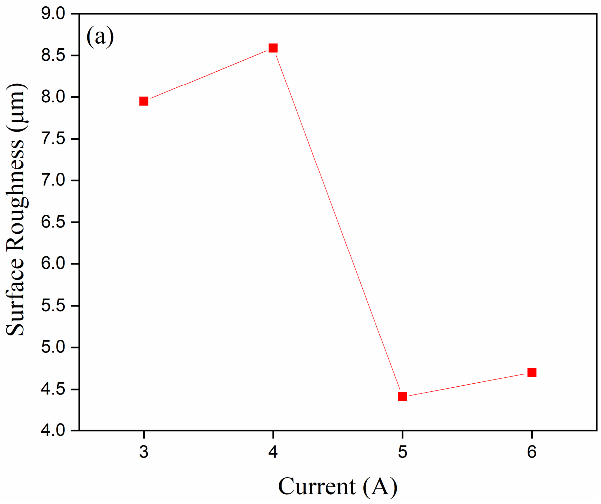

Figure 3 (a): The Effect of $I_c$on Surface Roughness.

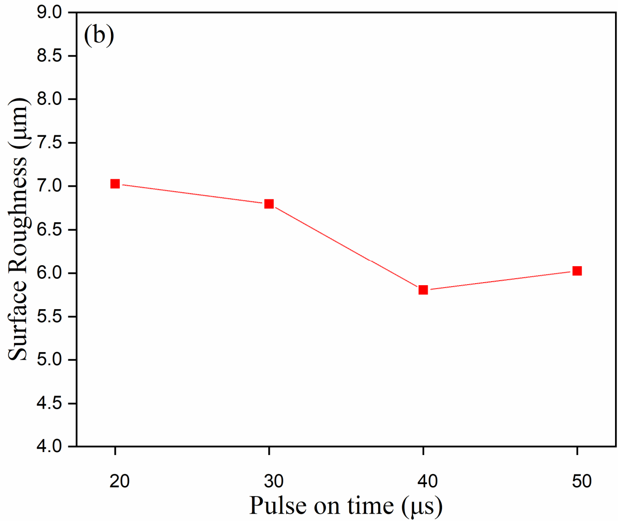

Figure 3 (b): The Effect of T_{on} on Surface Roughness.

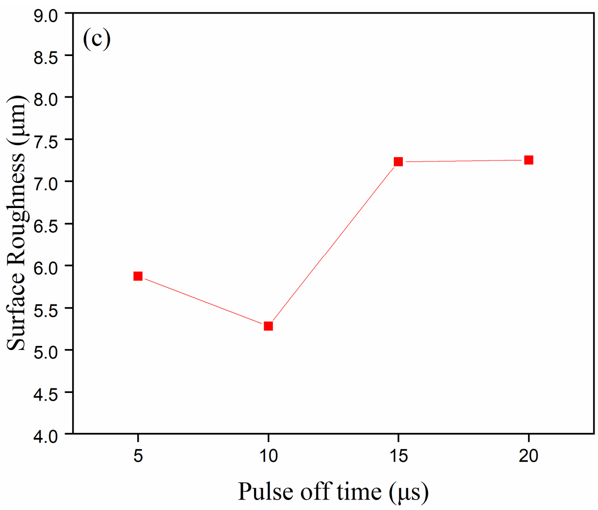

Figure 3 (c): The Effect of T_{off} on Surface Roughness.

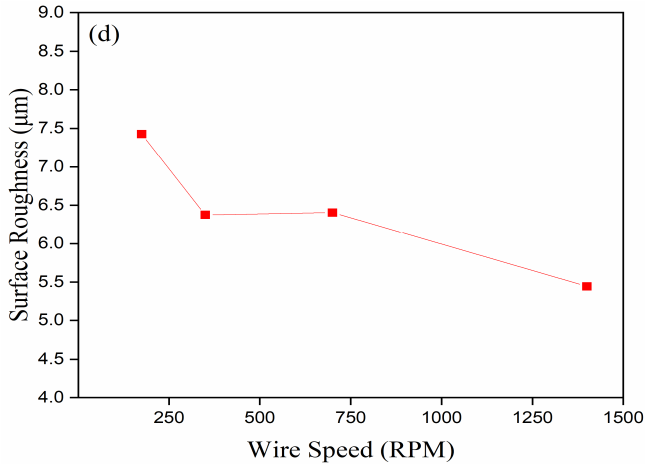

Figure 3 (d): The Effect of W_s on Surface Roughness.

Figure 3(b) shows that increasing the T_{on} from 20 µs to 40 µs reduced the SR from 7.025 µm to 5.805 µm. This is due to the increase in the intensity of the spark energy which increased duration of T_{on} as explained earlier in section 3.1. But, a further increase in T_{on} showed a slight increase in surface roughness by about 3.79 % due to reduced spark frequency as seen in figure 3(e). An increase in the T_{off} from 5 µs to 10 µs is found to reduce SR from 5.875µm to 5.285µmas shown in figure 3 (c). But, further increase in pulse-off time beyond 10 µs upto 15 µs resulted in a steady increase in SR and then it almost remained constant for 20 µs. This indicates that very short duration of T_{off} leads to promote high SR due to insufficient time available for flushing of the debris of machining before the beginning of next spark. Beyond the optimum duration of T_{off}-10 µs, the machining results in the formation of the recast layer due to reduced spark frequencies and non-machining time (T_{off}). Further, it is observed in figure 3(d) that, the SR decreased with an increase in the rotational speed of drum on which the electrode wire rotates. High SR values are seen at the drum rotation speed in the range from 175 RPM to 750 RPM. But, at 1400 RPM a very low SR value (5.44 µm) is achieved. This is due to the fact that the debris of machining is effectively removed by increasing the electrode wire-speed. The effective removal of debris prevented its recasting on the machined surface and hence reduced the surface roughness. Figure 3 (e) shows the effect of voltage on SR. It is observed that SR is increased by 7.35 % for change in voltage from 80 V to 90 V. This is because of the higher amount of energy discharged in each spark during the machining process.

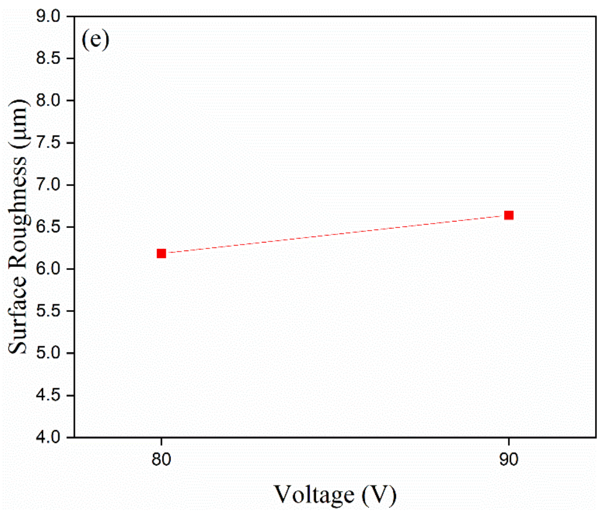

Figure 3 (e): The Effect of I_v on Surface Roughness.

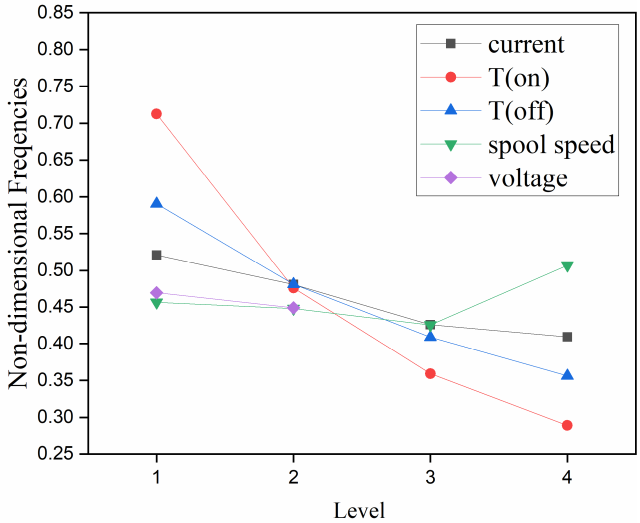

Figure 3 (f): The Spark Frequency at Different Levels of Process Parameters.

3.4 Analysis of Variance (ANOVA) of MRR

The SR obtained at different settings of the process parameters is analysed using statistical method. To identify process parameters which are significantly affecting SR, F-test is conducted on the ANOVA data at 95 % confidence. Table 5 shows the ANOVA of SR obtained in the present work. The F-values of the Ic, T_{off} and W_s are found to be higher than or close to the critical values of 3.63 for error degree of freedom 2. Hence their main effect on SR is significant in the chosen range of settings. Further, the percentage contribution of each process parameter is calculated. The $I_c$is the most significant parameter that contributed a maximum of 66.22 % variation to SR followed by T_{off} (13.88 %) and W_s (9.25 %). The effect of Voltage and Tonis 2.92 % and 4.90 % respectively are considered insignificant on SR in the chosen range of operating parameters.

Table 5: A NOVA for SR

Source	Degree of Freedom	Sum of Square	Mean Square	F
Current	3	56.1923	18.7308	23.64
Pulse-on time	3	4.1627	1.3876	1.75
Pulse-off time	3	11.7859	3.9286	4.96
Wire speed	3	7.8507	2.6169	3.30
Voltage	1	0.8281	0.8281	1.04
Residual Error	2	1.5850	0.7925	
Total	15	82.4047		

3.5 Optimum of Process Parameters

The levels of the process parameters are optimised to produce the low surface roughness while machining of IS 5986-Fe410 by wire-EDM. The average SR produced on the machined surface at different settings of process parameters is shown in table 6. From the table, it is observed that the minimum SR is achieved at the settings, current: level 3 (5A), pulse-on time: level 3 (40 µs), pulse-off time: 10 µs (level 2), drum/wire-speed: level 4 (1400 rpm) and voltage: level 1 (80 V). The predicted SR at this setting is 1.480µm. The confirmation experiments are conducted and test results are shown in the table 7. It is observed that SR obtained by the confirmation experiments are in close agreement with the predicted SR with an average deviation of 11.08 %. The maximum change (delta) in SR due to change in settings of

different process parameters at different levels is also shown in the same table. Based on the delta values, the process parameters are ranked in the order of their influence asI_c- I, T_{off}-II, W_s-III, T_{on} - IV, and I_v - V.

Table 6: The Average SR

Level	Current	Pulse-on Time	Pulse Off Time	Wire Speed	Voltage
1	7.950	7.025	5.875	7.425	6.185
2	8.590	6.795	5.285	6.375	6.640
3	4.410	5.805	7.235	6.405	
4	4.700	6.025	7.255	5.445	
Delta	4.18	1.22	1.97	1.98	0.455

Table 7: The Predicted and Experimental SR at Optimum Conditions

Trial	Predicted	Experimental	% Error
1	1.480 µm	1.667 µm	12.62 %
2	1.480 µm	1.618 µm	9.3 %
3	1.480 µm	1.689 µm	14.13 %
4	1.480 µm	1.640 µm	10.84 %
5	1.480 µm	1.627 µm	9.95 %

3.6. Mathematical Modelling of Surface Roughness

The generalised form of mathematical model to predict the dependent parameter is given by equation (2). A model is developed to establish the relationship between the wire-EDM control process parameters (x_1: Current, x_2: Pulse on time, x_3: Pulse off time, x_4: wire speed, x_5: voltage) and the response parameter i.e., SR. Ordinary least square method is used to estimate the model coefficients for the models established. Considering the main effect of process parameters, squared terms and their interaction effect, four different models are developed as given by the equation (3)-(6). The corresponding coefficients of determination (R^2) values of model 1, model 2, model 3 and model 4 are 79.88%, 87.57%, 90.10%, 89.59% respectively. The predicting accuracy of these models is tested by experimental data within the range of operating parameters (i.e., $3 \geq x_1 \leq 6$; $20 \geq x_2 \leq 50$; $5 \geq x_3 \leq 20$; $375 \geq x_4 \leq 1400$; $80 \geq x_5 \leq 90$).

$$
\begin{aligned}
& y = c + k_1 \times x_1 + k_2 \times x_2 + \ldots\ldots\ldots + k_n \times x_n \\
& Where, y - dependent\ \ parameter \\
& \qquad c - model\, constant \\
& \qquad x_1 \ldots\ldots. x_n - control\ parameter \\
& \qquad k_1 \ldots\ldots. k_n - coefficients\, of\ control\ parameters
\end{aligned}
\tag{2}
$$

$$SR = 0.21 - 1.287 \times I_c - 0.0293 \times T_{on} + 0.1853 \times T_{off} - 0.000779 \times W_s - 0.0074 \times I_v \tag{3}$$

$$
\begin{aligned}
SR = {} & 15.23 - 3.37 \times I_c - 0.277 \times T_{on} + 0.457 \times T_{off} + 0.00283 \times W_s - 0.0331 \times I_v \\
& + 0.305 \times I_c^2 + 0.00505 \times T_{on}^2 - 0.0096 \times T_{off}^2 - 0.000002 \times W_s^2
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
SR = {} & -111.1 + 36.06 \times I_c - 0.4365 \times T_{on} + 0.7379 \times T_{off} + 0.02468 \times W_s + 1.302 \times I_v \\
& + 0.55 \times I_c^2 + 0.007573 \times T_{on}^2 - 0.01882 \times T_{off}^2 - 0.000013 \times W_s^2 - 0.09164 \times I_c \times T_{on} \\
& - 0.1632 \times I_c \times T_{off} + 0.000111 \times I_c \times W_s - 0.4242 \times I_c \times I_v + 0.01640 \times T_{on} \times T_{off}
\end{aligned}
\tag{5}
$$

$$SR = 11.38 - 0.96 \times I_c + 0.123 \times T_{off} + 0.00378 \times W_s - 0.0560 \times I_c \times T_{off} - 0.00293 \times I_c \times W_s - 0.000494 \times T_{off} \times W_s + 0.000251 \times I_c \times T_{off} \times W_s \quad (6)$$

Table 8 shows the SR values, predicted values (P_a) from the models and its corresponding prediction errors (P_{err} %) for different test conditions. The maximum, minimum and average prediction error (%) of SR for different models is shown in figure 4. It is observed that model 4 given by equation (6) provides the realistic prediction of SR compared to the other models developed for prediction with average error of 8.59 %. Further, the distribution of residuals over the line of fit is shown in figure 5 (a). It is observed that residuals are distributed around the line of fit linearly and the developed model satisfies the mandatory condition of linearity of the residual distribution. Figure 5 (b) shows the standardized effects of different model parameters and their interaction effect. It is seen that the parameters such as current, T_{off} and interaction effect of I_c, T_{off}, W_s are highly significant in the model for predicting the SR.

Table 8: The Predicting Accuracy of Different Mathematical Models

Test conditions					Expt R_a	Model 1		Model 2		Model 3		Model 4	
I_c	T_{on}	T_{off}	W_s	I_v		P_a	P_{err} %	P_a	P_{err} %	P_a	P_{err} %	P_a	P_{err} %
2	10	5	1400	80	6.82	6.58	3.53	6.884	0.93	5.85	14.11	6.65	2.36
2	20	10	700	80	6.98	7.76	10.11	8.153	16.80	6.71	3.78	8.17	17.04
2	30	15	350	90	8.8	8.59	2.35	8.407	4.47	8.70	1.05	8.93	1.58
2	40	20	175	90	9.2	9.36	1.79	9.465	2.88	9.15	0.52	9.34	1.56
3	10	10	350	90	7.82	6.97	12.18	6.977	10.78	7.72	1.25	7.20	7.89
3	30	20	1400	80	7.64	7.49	1.95	6.794	11.07	6.67	12.67	7.83	2.59
3	40	15	700	80	8.78	6.81	28.75	7.913	9.87	8.51	3.06	7.03	19.84
4	10	15	175	80	6.64	6.82	2.64	6.846	3.10	6.58	0.85	5.97	10.02
4	20	20	350	80	5.36	7.31	26.74	6.508	21.40	5.25	1.8	6.31	17.74
4	30	5	700	90	3.04	3.89	22.01	2.932	3.55	2.76	9.08	3.26	7.30
4	40	10	1400	90	2.6	3.98	34.77	4.303	65.50	1.62	37.5	2.55	1.76
5	10	20	700	90	6.82	5.97	14.11	7.062	3.54	6.53	4.18	6.48	4.91
5	20	15	1400	90	4.72	4.21	12.06	4.243	10.10	3.738	20.80	4.98	5.67
5	30	10	175	80	3.74	4.02	6.981	3.636	2.78	3.680	1.61	4.44	18.70
5	40	5	350	80	3.52	2.66	32.09	3.148	10.58	3.418	2.91	3.32	5.61

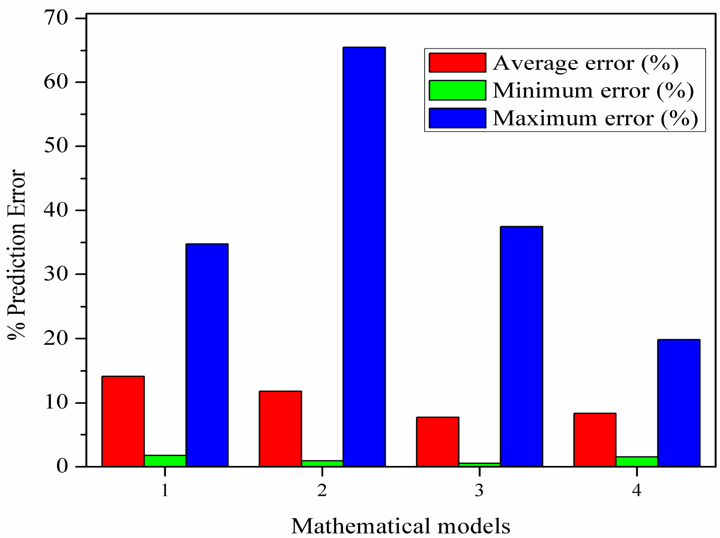

Figure 5: Comparison of Mrr Predicted by Regression Model with Experiments Values.

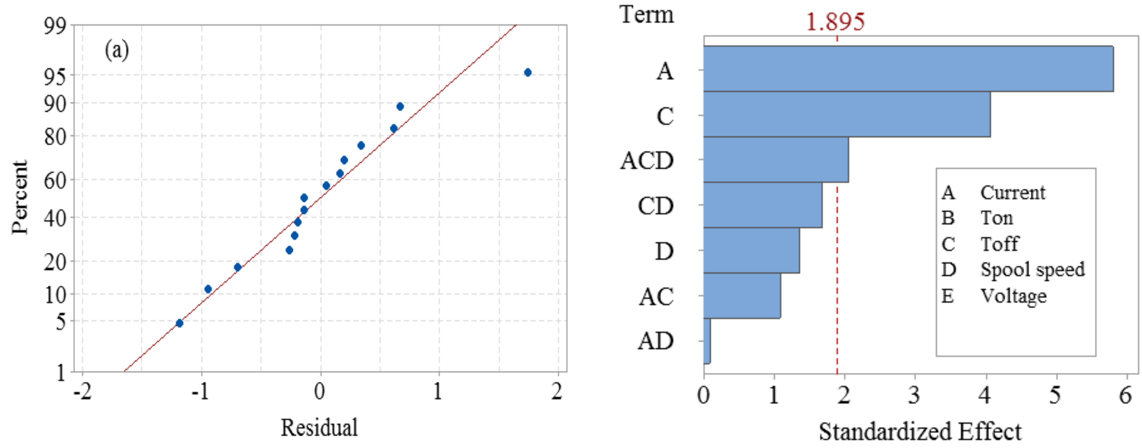

Figure 5 (a): Normal Probability Plot. (b) Pareto Chart of the Standardized Effects.

4. CONCLUSIONS

Based on the wire-EDM of IS 5986 Fe 410 steel, the following conclusions are drawn.

- The process parameters such as current, pulse-off time and wire-speed showed significant influence on SR. The contribution of process parameters on SR are the current - 66.22 %, pulse-off time - 13.77 %, wire speed - 9.25 %, pulse-on time - 4.90 %, voltage - 2.92 %.
- The optimum settings which produced the minimum SR (1.480 µm) are current: 5 A, pulse-on time: 40 µs, pulse-off time: 10 µs, drum/wire-speed - 1400 rpm and voltage - 80 V.
- The regression models are developed to predict the SR within the operating range (3 A $\geq x_1 \leq$ 6 A; 20 µs $\geq x_2 \leq$ 50 µs; 10 µs$\geq x_3 \leq$ 25 µs; 375 rpm$\geq x_4 \leq$ 1400 rpm; 80 V $\geq x_5 \leq$ 90 V) with R^2 values 89.30 %. The model predicting accuracy is verified by experiments results and average predication error is 11.08 %.

ACKNOWLEDGEMENTS

Authors are grateful to Manipal Institute of Technology, Manipal Academy of Higher Education, India, for providing the laboratory and material support to carry out this research work.

REFERENCES

1. *J. Nomani, A. Pramanik, T. Hilditch, G. Little fair, Machinability study of first generation duplex (2205), second generation duplex (2507) and austenite stainless steel during drilling process, 2013, Wear, vol-304 (1), pp.20–28.*
2. *J. Nomani, A. Pramanik, T. Hilditch, G. Little fair, Machinability study of first generation duplex (2205), second generation duplex (2507) and austenite stainless steel during drilling process, 2013, Wear, vol- 304 (1–2), pp. 20–28, https://doi.org/10.1016/j.wear.2013.04.008.*
3. *S. Dolinšek, Work-hardening in the drilling of austenitic stainless steels, J. Mater. Process. Technol., 2003, vol-133 (1), pp. 63–70.*
4. *L. Jiang, J. Paro, H. Hänninen, V. Kauppinen, R. Oraskari, Comparison of grindability of HIPed austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 stainless steels using alumina wheels, J. Mater. Process. Technol., 1996, vol-62 (1–3), pp.1–9.*

5. D. O Sullivan, M. Cotterell, Machinability of austenitic stainless steel SS303, J. Mater. Process. Technol., 2002, vol-124 (1), pp.153–159.
6. J. Paro, H. Hänninen, V. Kauppinen, Tool wear and machinability of HIPed P/M and conventional cast duplex stainless steels, 2001, Wear 249 (3), pp. 279–284.
7. J. Nomani, A. Pramanik, T. Hilditch, G. Littlefair, Investigation on the behaviour of austenite and ferrite phases at stagnation region in the turning of duplex stainless steel alloys, Metallurg. Mater. Trans. A, 2016, vol-47 (6), pp. 3165–3177.
8. J. Nomani, A. Pramanik, T. Hilditch, G. Littlefair, Stagnation zone during the turning of duplex SAF 2205 stainless steels alloy, Mater. Manuf., 2017, vo. 32 (13), pp. 1486–1489
9. S. Raghavan, S. Melkote, and F. Hashimoto, Laser tempering based turning process for efficient machining of hardened AISI 52100 steel, J. Manuf. Process., 2013, vol. 15, no. 3, pp. 318–328.
10. A. Alshemary, A. Pramanik, A. K. Basak, and G. Littlefair, Accuracy of duplex stainless steel feature generated by electrical discharge machining (EDM), Meas. J. Int. Meas. Confed., 2018, vol. 130, pp. 137–144.
11. Ajay, C. V., & Guru, T. C. An Analysis of Performance Parameters and Effect of Copper Tungsten and Graphite Electrodes on h13 Tool Steels in EDM.
12. J. R. Gamage, A. K. M. DeSilva, C. S. Harrison, and D. K. Harrison, Process level environmental performance of electro discharge machining of aluminium (3003) and steel (AISI P20), J. Clean. Prod., 2016, vol. 137, pp. 291–299.
13. Deepak, D. Shrinivas, P, Hemant, G, Iasy, R, Optimisation of current and pulse duration in electric discharge drilling of D2 steel using graphite electrode, International Journal of Automotive and Mechanical Engineering, 2018, vol. 15(4), pp. 5914–5926.
14. Doreswamy, D., Javeri, J. Effect of process parameters in electric discharge machining of D2 steel and estimation of coefficient for predicting surface roughness, International Journal of Machining and Machinability of Materials, 2018, vol-20(2), pp. 101–117.
15. Anjaiah Devineni, Deepak Doreswamy, Akash Valavala, Natt Winitthumkul, Machining of D2 heat treated steel using abrasive water jet: the effect of standoff distance and feed rate on kerf width and surface roughness, International Journal of Research in Engineering and Technology, 2014, vol-3(8), pp. 417–421.
16. Umanath, K., Devika, D., & Seshabhattur, S. A Review on Abrasive Water Jet Milling of High Strength Materials.
17. Y. Zhu, J. Chen, H. Xu, L. Gu, and W. Zhao, Research on the Surface Quality of the Blasting Erosion Arc Machined Stainless Steel, Procedia CIRP, 2016, vol. 42(1), pp. 252–256.
18. F. Klocke, S. Harst, M. Zeis, and A. Klink, Modeling and Simulation of the Microstructure Evolution of 42CrMo4 Steel during Electro Chemical Machining, Procedia CIRP, 2018, vol- 68, pp. 505–510.
19. Tajdeen, A., Megalingam, A., Kumar, M., & Kumar, B. S. Multiresponse Optimization of Drilling Process Parameters of az 31 Magnesium Alloys Using Gray Relational Analysis Technique.
20. Silambarasan, S., & Prabhakaran, G. Optimization of Process Parameters of Wire EDM using Genetic Algorithm. Carbon, 100, 0–036.

AUTHOR'S PROFILES

Deepak D. is Associate Professor in the department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, India. He has obtained B.E (2003), M. Tech (2005) in Manufacturing Engg. from National Institute of Engineering, Mysore and Ph. D from Manipal University, India. His area of research includes CFD analysis and advanced manufacturing process. He has published about 20 international journal and conference articles. He has received a certificate of merit for his research article in World Congress of Engineering 2012 held at Imperial college, London, UK. He is a member of International Association of Engineers (IAE)

Dr Rajendra Beeduis Professor in the department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, India. He has obtained Ph.D from NIT, Suratkal, India. His area of research includes manufacturing process and mechanical Vibrations. He has published about 28 international journal and conference articles. He has about 35 years of teaching experience and published one text book on Engineering Graphics.